Assessing the Ecological Risk of Creating Artificial Reefs from ex-Warships

R.K. Johnston[1]*, H. Halkola[1], R.George[1], C. In[1], R. Gauthier[1], W. Wild[1], M. Bell[2] and R. Martore[2]

[1]Space and Naval Warfare Systems Center Code 2362
53475 Strothe Rd. Bldg. 111 RM 258
San Diego, CA 92152-6326 USA
*Corresponding Author: johnston@spawar.navy.mil

[2]South Carolina Department of Natural Resources
PO Box 12559
Charleston, SC 29422-2559

Abstract- Inactive warships would make excellent artificial reefs in coastal waters if preliminary data suggesting that they pose no threat to human health or the environment from contamination can be confirmed. A screening level ecorisk assessment was conducted on data from artificial reefs composed of ex-warships located off the coast of South Carolina to assess the potential risk of contamination from sunken warships. Contaminants of concern (COCs) can enter the system from releases from the sunken vessel or inputs from coastal waters. The assessment endpoints were the reef community and organisms that may frequent and forage on the reef. Primary exposure can occur to the reef community, which is composed of demersal fishes, epibenthic and benthic invertebrates, and primary producers and zooplankton. Indirect exposure can occur through bioaccumulation in the food chain to avian omnivores, avian piscivores, and marine mammals. Benchmarks were developed for water, sediment, tissue residue, and dietary exposures. Estimates of exposure associated with ex-warship reefs were compared to estimates of exposure associated with (ii) other artificial reefs, (iii) natural reefs, and (iv) regional background and compared to the appropriate ecological effects benchmarks.

I. INTRODUCTION

The anticipated benefits of building reefs with former warships (REEFEX) includes enhancing ecological resources by increasing the amount of productive hard-bottom habitat, using artificial reefs as marine protected and conservation areas, or using artificial reefs to provide alternative reefs for recreational fishing and diving so that natural reefs can be protected and conserved [1]. Artificial reefs can also provide economic benefits to local communities by increasing tourism and commercial activities associated with fishing and diving on the reef [2]. The Rand Corporation [3] concluded that more than $1.5 billion taxpayer dollars would be saved if decommissioned ships were "reefed" instead of "scrapped." However, there is concern that sunken ships could leach polychlorinated biphenyls (PCBs) and other contaminants that could impact ecological resources. The EPA has the authority to approve risk-based disposal of PCBs [4], if a finding of no unreasonable risk of injury to human health and the environment can be made. This paper reports on the potential ecological risks of contaminants that could be released from sunken warships.

Contaminants can enter the system through releases from the sunken vessel and inputs from coastal waters (Fig. 1). Primary exposure can occur to the reef community, which is composed of demersal fishes, epibenthic and benthic invertebrates, and primary producers and zooplankton. Indirect exposure can occur through bioaccumulation in the food chain to avian omnivores, avian piscivores, and marine mammals. The primary data used in the assessment included metals and PCBs measured in fish and invertebrate tissues collected from artificial reefs off the coast of South Carolina [5] (Fig. 2), PCBs measured in fish collected from

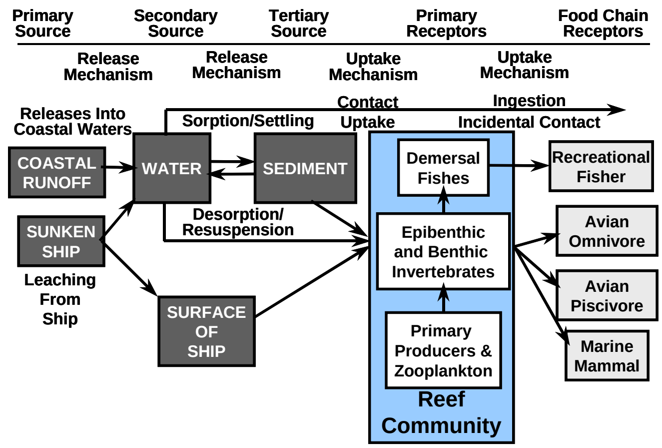


Fig. 1. Exposure pathways and assessment endpoints.

an ex-Navy ship reef (ex-USS VERMILLION LKA 107) and a reference reef [6], and data from laboratory leaching experiments on solid materials containing PCBs that could be on ex-Navy warships [7]. Background data for the ecorisk screening were obtained from the Environmental Monitoring and Assessment Program (EMAP) Estuaries conducted for the Carolinian Province [8].

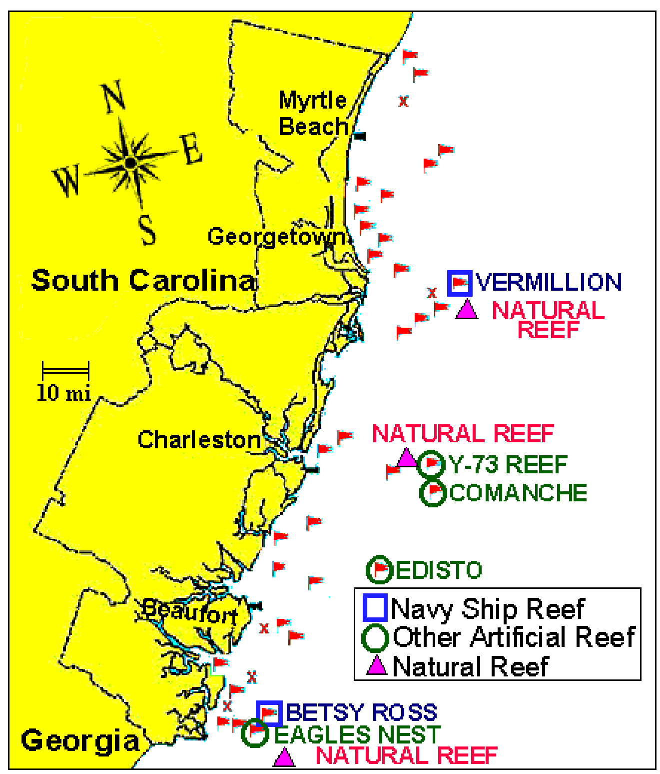


Fig. 2. Locations of artificial reefs (flags) and reefs sampled by SCDNR [5] off the coast of South Carolina, USA.

This work was sponsored by the Chief of Naval Operations, Code N4561, Arlington, VA.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 SEP 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Assessing the Ecological Risk of Creating Artificial Reefs from ex-Warships**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Space and Naval Warfare Systems Center Code 2362 53475 Strothe Rd. Bldg. 111 RM 258 San Diego, CA 92152-6326 USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002146. Oceans 2003 MTS/IEEE Conference, held in San Diego, California on September 22-26, 2003. U.S. Government or Federal Purpose Rights License, The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

II METHODS

The study area encompasses an area of the inner continental shelf along South Carolina, USA (Fig. 2). It includes the locations of the vessels sampled by the South Carolina Department of Natural Resources (SCDNR). The dynamic and heterogeneous nature of the study area calls for a regional approach to control for spatial variability. The locations evaluated included: artificial reefs composed of former warships (Navy Ship Reef □), artificial reefs composed of materials other than former warships (Other Artificial Reef ○), naturally occurring hard bottom areas (Natural Reef ▲), and nonreef areas representative of regional or background conditions (Carolinian Province Background).

Benchmarks of effects for water (W_B), and sediment (S_B) concentrations and fish (T_{Fish}) and invertebrates (T_{Invert}) tissue residues were developed (Table 1). The tissue benchmarks were for the bioaccumulation critical value (B_{CV} – the tissue concentration that suggests water quality criteria was exceeded) [9], tissue-screening value (TSV – the tissue concentration below which ecological effects are not expected) [10], critical body residues obtained from [11] corresponding to the no observed effect dose (NOED) and the lowest observed effect dose (LOED), and the no observed adverse effect levels (NOAEL) for dietary consumption of prey by osprey (D_O), black duck (D_{BD}), and dolphin (D_D) [6]. Fish and invertebrate tissue residues were compared to the effects benchmarks. Risks to primary producers and zooplankton were evaluated by conservative benchmarks protective of aquatic life (TSV, B_{CV}). Risks to demersal fish and reef invertebrates were evaluated by critical body residues (NOED, LOED). Risks to the food chain receptors (dolphins, omnivores, and piscivores, Fig. 1) were evaluated by comparing prey tissue concentrations to dietary benchmarks and assuming that 100% of the predators' diet consisted of prey sampled from the reefs.

To provide additional data for completion of the ecological [6] and human health [12] risk assessments, three species of fish commonly caught by sports fishers vermillion snapper (VS – *Rhomboplites aurorubens*), white grunt (WG – *Haemulon plumieri*), and black seabass (BSB – *Centropristis striata*), were collected from the ex-VERMILLION Reef and a natural hard bottom reef located about 4 nm from the ex-VERMILLION (Reference Reef, Fig. 2) [5, 8]. Fillets from the fish were analyzed for lipids, 30 individual PCB congeners, 10 homologues, and total PCB.

TABLE 1. TISSUE RESIDUE BENCHMARKS (µg/g DRY WEIGHT).

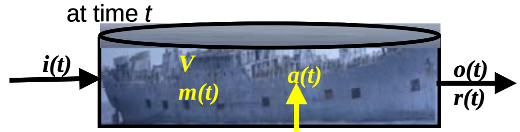
	Fish Tissue (T_{Fish})						
Chem	B_{CV}	TSV	NOED	LOED	D_{BD}	D_O	D_D
Cd	2.4	0.2	1.6	3.6	64	32	
Cr	3.2	0.7	0.7	1.7	44	22	
Cu	2.5	12.0	0.3	3.2	2089	1044	108.1
Ni	1.5	1.5			3440	1720	
Pb	1.6	0.3	10.2	16.1	50	25	
Zn	15.2	80.0			644	322	
PCB	24.3	1.7	6.0	7.2	8	4	1.3
	Invertebrate Tissue (T_{Invert})						
Cd	186.0	0.2	4.5	6.5	81		
Cr	20.0	0.9	0.7	7.2	56		
Cu	62.0	15.0	36.0	40.5	2611		135.2
Ni	16.4	1.9	14.2	141.5	4300		
Pb	81.0	0.3	20.0	101.8	63		
Zn	1620.0	100.0			806		
PCB	4.7	2.2	3.0	5.5	10		1.6

No sediment data from the South Carolina study area were available for the assessment, so sediment data from a study of the ex-USS AGERHOLM DD 826 were used to screen sediment exposure levels. Sunk during a military weapons test in 1982 (SINKEX), the ex-AGERHOLM sits on the bottom, largely intact, at a depth of 2,750 ft (838 m) about 120 miles (193 km) off the coast of San Diego, CA [13]. Concentrations of chemicals measured in sediment obtained near the hull of the ex-AGERHOLM (Inner Ring) and a reference location 1 km away from the hull (Outer Ring) were used to calculate hazard quotients by dividing the measured concentrations by the Effects Range Low (ERL) effects benchmarks for sediment [14].

Empirical estimates of PCB leaching rates measured for felt gaskets, electric cable, paint, rubber, foam insulation, oils and greases, bulkhead insulation, and pure Aroclors [7] were used to simulate the leaching of PCBs from the ex-VERMILLION and estimate the instantaneous steady state concentration of total PCB around the ship (Fig. 3). Based on information available about the types of materials and PCB concentrations estimated to be present on the ex-AGERHOLM [15], low, average and high PCB loading scenarios were developed to simulate the leaching of PCBs from the ex-VERMILLION. The estimated concentrations were compared to the PCB water benchmarks and multiplied by bioconcentration factors to project the resulting PCB concentration in fish and shellfish.

The model parameters were estimated as follows. The volume of water that contains the ship was determined from the dimensions of the ex-VERMILLION: length 139.95 m (459 ft 2 in), beam 19.20 m (63 ft), and height 16.76 m (55 ft) as 45,052,457 liters (45,052.5 m^3). The average current velocity was obtained from the South Atlantic Bight Synoptic Offshore Observational Network (SABSOON), which is a real-time oceanographic observational network located on the southeastern continental shelf of the U.S. [16]. Current data from Station M2 of the SABSOON network were used to estimate bottom currents at the ex-VERMILLION reef. Located about 60 miles offshore of Savannah, GA, Station M2 records bottom currents at about the same depth (28 m, 91 ft) and location on the continental shelf as the ex-VERMILLION reef. The long-term average current velocity observed for bottom currents at Station M2 was 0.35 m/s (30,240 m/day) [16].

V = Well mixed volume of water around the ship
m(t) = mass of PCBs present in water around ship at time *t*



a(t) = rate of leaching from solids containing PCB on the sunken ship
o(t) = ***i(t)*** = Rate of exchange with surrounding water
r(t) = mass of PCBs removed due to flushing at time *t*
Other loss terms = 0

Fig. 3. Model used to estimate the concentration of PCBs in a well-mixed volume of water around a sunken ship.

Conclusions were based on the evidence of potential ecological harm, evidence of exceeding reference and background levels, and the degree to which data were available to support the assessment. The more harmful and elevated above reference and background the exposure was, the higher the risk. The reliability of the data was based on how much data were available, how quantitative the data were, and how well the data represented site conditions, spatial differences, temporal or seasonal variations, and responses from the stressors.

III RESULTS

Tissue residue data showed that exposure to PCBs, Pb, and Cd in tissues of fish and PCBs and Pb in invertebrates were higher in samples from Navy ship reefs (Fig. 4) than reference reefs. Most of the residue data were below effects levels for the reef community suggesting that there was negligible to low risk of exposure to demersal fish and reef invertebrates. There were physical and physiological differences between the fish from the reference and target reefs. Fish from the ex-VERMILLION reef had larger livers, higher hepatosomatic index, and fish from the reference reef had significantly less lipid content. On a dry weight basis, there were significantly higher PCB levels in black sea bass (BSB), vermillion snapper (VS), and white grunt (WG) sampled from ex-VERMILLION reef (Fig. 4). The PCB levels were not correlated to the hepatosomatic index. For food chain receptors, data on contaminant concentrations in prey were below dietary benchmarks suggesting that there is low risk of exposure to dolphins and fish eating birds, and negligible risk of exposure to diving birds. There was high confidence of negligible to low exposure to PCBs because supplemental fish sampling and analysis for PCBs was conducted for the assessment. Owing to limited data available for screening, the confidence in the conclusions for the other chemicals of concern was low.

Hazard quotients calculated for sediment data obtained from the ex-AGERHOLM study [13] showed that Cd, Cu, Ni, Ag, and Zn were higher in samples from the inner ring. Samples from the inner ring for Cd, Cu, Ni, and Zn exceeded the ERL and Ni concentrations exceeded the Effect Range Median [14]. The risk of sediment exposure was negligible for PCB, PAH, Cr, Hg, and Pb; low for Ag and Zn; medium for Cd and Cu; and adverse for Ni. Because the sediment benchmarks for Ni are overprotective [14], the finding of adverse exposure for Ni may be overly conservative. Data reliability for the sediment screening was good. Only one study was conducted at the SINKEX Site [13], but there were multiple sampling events (between 1998 and 1999), ten stations were sampled on the inner ring, eight stations were sampled on the outer ring, and all the data reported met the data quality objectives of the SINKEX study [13].

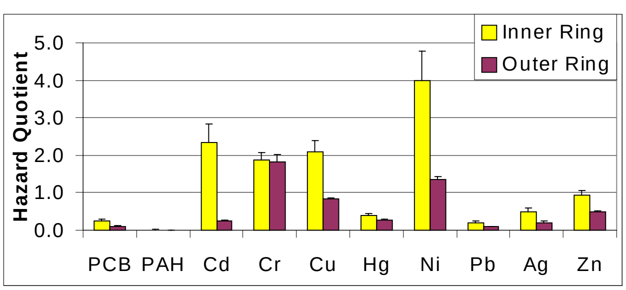


Fig. 5. Hazard quotients obtained for contaminants measured in deep-sea sediments collected 3 m (Inner Ring) and 1 km (Outer Ring) from ex-AGERHOLM [13].

Empirical estimates of PCB leaching rates were used to simulate the leaching of PCBs from the ex-VERMILLION and estimate the instantaneous steady state concentration of total PCB around the ship. Because the empirical leaching rate of PCBs from oils and greases was not available, the leaching rate of pure Aroclor 1254 [7] was used in the model as an analogue for PCBs dissolved within residual oils and greases remaining on the ship following purging of fuel tanks and reservoirs [15]. The model showed that residual oils and greases and bulkhead insulation were the most important sources of PCB loading [6]. The estimated concentrations were compared to the PCB water benchmarks (0.03 ug/L for chronic and 10.0 ug/L for acute exposure [17]) and multiplied by bioconcentration factors to project the resulting PCB concentration in fish and shellfish (Table 2). The results showed that there was negligible risk of exceeding water column or tissue benchmarks (Table 1) for any of the loading scenarios evaluated.

TABLE 2. CONCENTRATION OF TOTAL PCB RESULTING FROM STEADY STATE MODEL SCENARIOS.

Loading Scenario	Water µg/L	Fish ng/g dry	Invertebrate ng/g dry
Low	7.94×10^{-8}	0.06	0.01
Average	2.58×10^{-6}	2.09	0.40
High	5.99×10^{-6}	4.85	0.93

The results from the empirical leaching studies and hypothetical steady state model were used to evaluate the consequences of removing materials from the ship to reduce PCB loading (Table 3). In general, removing the materials with the highest leach rates would result in the greatest reduction in PCB loading per unit material removed. Based on the empirical upper bound of the leach rate obtained from the solids tested [7] removing 1 g of pure Aroclor 1254 would reduce leaching by the same amount as removing 4 g of pure Aroclor 1268, 143 g of bulkhead insulation, 1.855 kg of foam insulation, 3.8 kg of felt gaskets, 5.3 kg of rubber products, 56.5 kg of paint, or 80 kg of electrical cable (Table 3.A). For the solid materials tested in the laboratory leaching experiments, the effect of decreasing PCB loading by reducing the amount of solid materials containing PCBs was evaluated using the steady state model. The steady state model takes into account both the quantity and concentration of PCBs in the materials estimated to be on the ship when it was sunk. Based on the average loading scenario, removing about 150 g of bulkhead insulation would result in about the same reduction in PCB loading as removing about 4 kg of felt gaskets, 30 kg of foam insulation, 200 kg of electrical cable, 300 kg of rubber products, or 500 kg of paint (Table 3.B).

IV DISCUSSION

The sources of uncertainty in the ecorisk screening assessment included the implicit assumptions used to formulate the conceptual model, the uncertainty in interpreting critical values and benchmark concentrations, the complexities associated with multiple contaminant stressors, and the uncertainties arising from the lack of data and toxicological information on key components of the assessment endpoints used in the screening-level risk assessment.

Differences in PCB concentrations measured in fish from Navy ship reefs and natural reefs may have more to do with the availability of food and foraging behavior of fish on the reefs than uptake of contaminants leached from the ship. The Vermillion Reef is

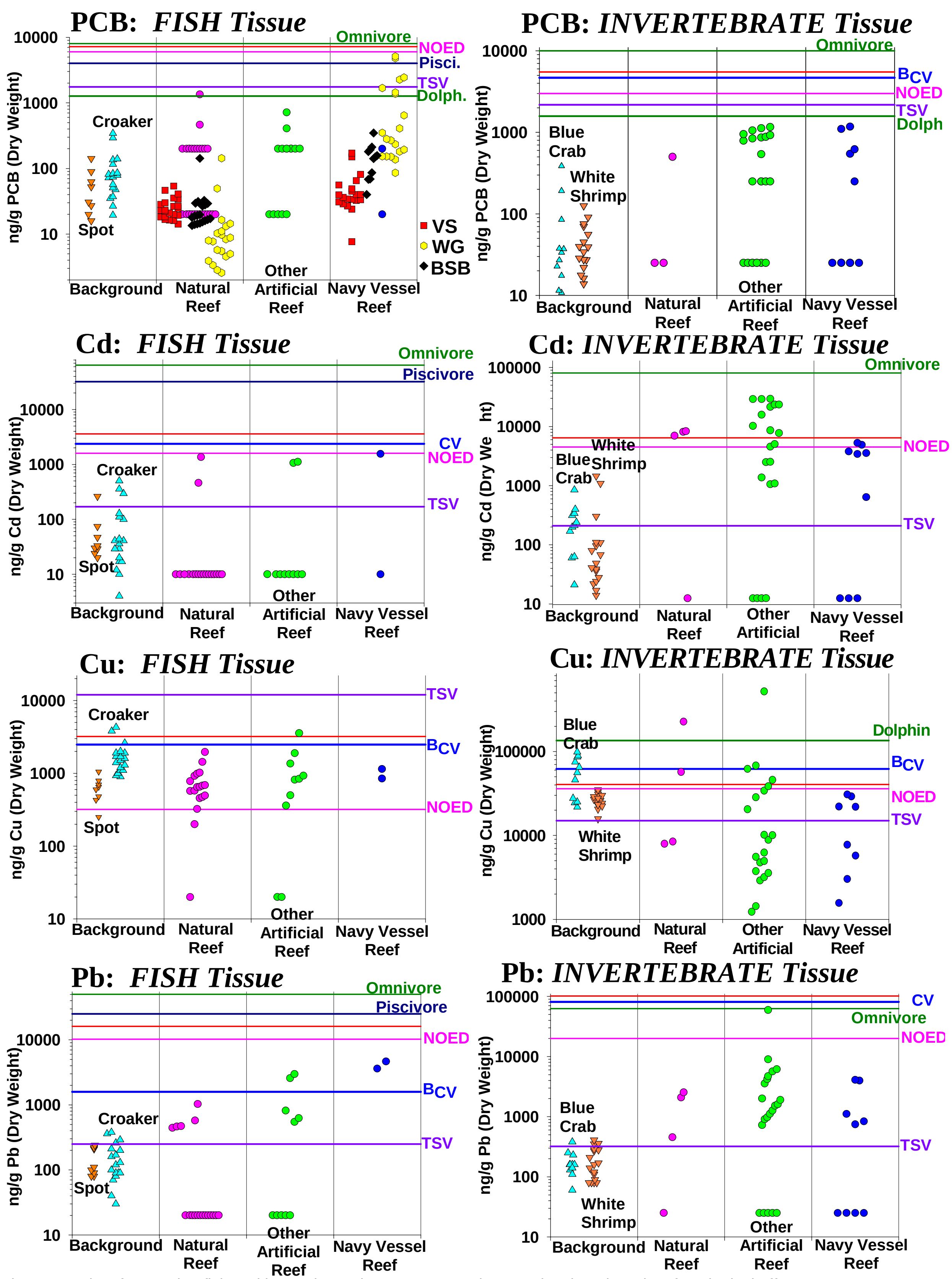


Fig. 4. Results of screening fish and invertebrate tissue concentrations against benchmarks of ecological effects.

TABLE 3. THE DECREASE IN PCBS RELEASED AS A RESULT OF REMOVING DIFFERENT AMOUNTS OF SOLID MATERIALS CONTAINING PCBS USING LABORATORY RESULTS (A) AND THE AVERAGE STEADY STATE MODEL DEVELOPED FOR THE EX-VERMILLION (B).

Material	Material Containing PCBs	Total Weight of PCBs	Fraction PCB	Leaching rate of PCB	Leaching rate of PCB	Release Rate (a)	**AMOUNT REMOVED**	***DECREASE in RELEASE***
A. Laboratory Results	Kg	g PCB in solid	g PCB/g of solid	ng of PCB/ g solid/day	ng PCB/ g PCB in solid/ day	ng PCB released/day	Kg solid removed	ng PCBs released/day
Felt Gaskets				0.93			3.769	3,505.35
Electric Cable				0.044			79.667	3,505.35
Paint				0.062			56.538	3,505.35
Rubber				0.66			5.311	3,505.35
Foam Insulation				1.89			1.855	3,505.35
Pure Aroclor 1254				3505.35			0.001	3,505.35
Pure Aroclor 1268				838.00			0.004	3,505.35
Bulkhead Insulation				24.45			0.143	3,505.35
Oils & Greases				No Empirical Data				
B. Model Results								
Felt Gaskets	151.2	30,298	0.20041	0.93	4	122,511	4.326	3,505.35
Electric Cable	50,559.7	22,299	0.00044	0.044	37	817,641	216.757	3,505.35
Paint	186,255.9	9,146	0.00005	0.062	144	1,318,797	495.066	3,505.35
Rubber	4,989.0	140	0.00003	0.66	413	57,623	303.494	3,505.35
Foam Insulation	30.2	15	0.00050	1.89	212	3,210	30.236	3,210.49
Bulkhead Insultation	30.2	13	0.00044	24.45	55,568	739,279	0.143	3,505.35

[a] All material removed from ship

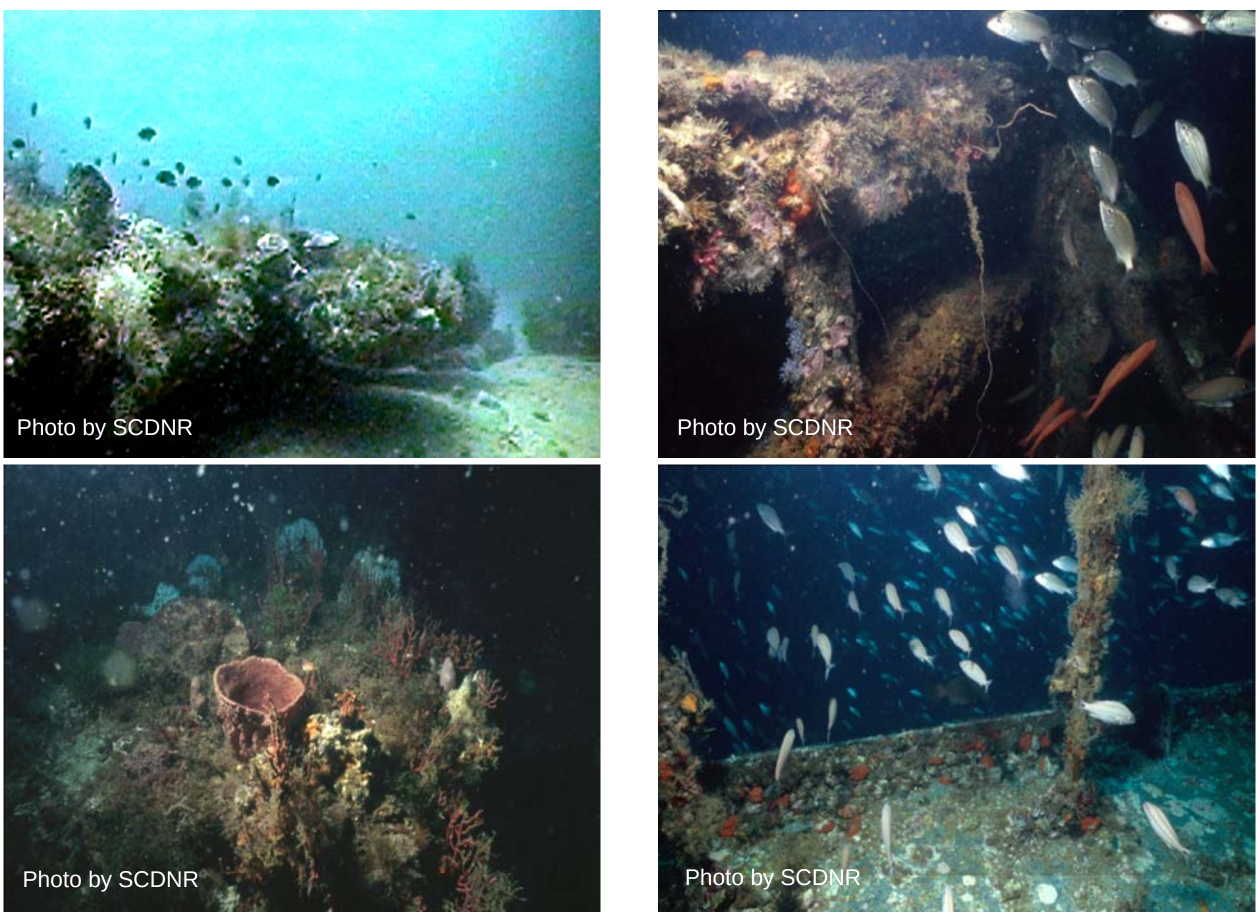


Fig. 6. Differences in structure of natural reefs (left panels) and Navy ship reefs (right panels).

about 140 m long and provides high relief up to about 17 m. The reference reef is a relatively small area (45 m long) of naturally occurring hard bottom or "live bottom," consisting of intermittent rocky outcroppings with low to moderate relief (extending to 2.4 m). The higher relief and greater size of the artificial reef may provide more habitat for development of epibenthic biomass comprising different links in food chain than is present on the natural reef (Fig. 6). Since all specimens were collected at about the same time, it is unlikely that spawning or migration could account for the differences measured. It may be hypothesized that something related to feeding behavior, such as more concentrated food on the artificial reef, less energy consumed by the fish living at the artificial reef, and plenty of crevices and compartments on the artificial reef to easily avoid predators could cause the observed differences. White grunt feed lower on the food chain than vermillion snapper and black sea bass so it is reasonable to suspect that white grunt are feeding on prey that are in closer proximity to the reef and spend more time on the reef than vermillion snapper and black sea bass. The largest fish collected were white grunts caught on the Vermillion Reef and these were the fish with the highest levels of PCBs (Fig. 4).

There is uncertainty about the tissue residue benchmarks used to screen the fish and invertebrate tissue data. Many of the tissue residue benchmarks were derived from toxicity data on freshwater species [11] because toxicity data on reef organisms are not widely available. The TSV represents a conservative initial screening value capable of eliminating chemicals that do not pose significant risks to aquatic biota. If a TSV is exceeded it does not necessarily mean that an observed tissue concentrations poses an adverse risk to biota, rather it indicates that the chemical requires a more detailed evaluation in later phases of the ecological risk assessment [18]. Uncertainty factors were used to account for some of the uncertainty, but in many cases application of the uncertainty factors may make the conclusions overly conservative. The assumption that food chain receptors would consume 100% of their diet from the target reefs is very conservative. The dietary benchmarks were based on prey consumption and direct ingestion of surface water and sediment were not included. Exposure from incidental contact with sediment would be negligible for predators in the reef environment.

There was a fair amount of uncertainty in using data from the deep ocean study of the ex-AGERHOLM to infer sediment exposure conditions that could occur at a shallow water artificial reef. The lower temperature and higher pressure at the deep ocean site results in lower leaching rates of PCBs from solid materials than the laboratory leach rates measured under warmer and shallower water artificial reef conditions [7]. On the other hand, the isolated environment at the deep ocean site effectively creates a "closed" system for evaluating contaminant accumulation in the sediment than would occur at a shallow water reef with much greater currents, open water exchange, and dissipation of contaminants released from the ship. Furthermore, there is also uncertainty about other sources of coastal pollution present in the shallow water reef environment. The ex-AGERHOLM site is more of a depositional environment (sedimentation rates of 0.03 – 0.07 cm/yr, [13]) than the reefs studied off the coast of South Carolina, which are subject to erosive forces like hurricanes and other sediment transport processes.

There is also uncertainty associated with the sediment benchmarks and their applicability to evaluate exposure to deep ocean (SINKEX) and shallow ocean (REEFEX) organisms. Because the ERL and ERM were developed from studies conducted in near coastal and estuarine systems, the benchmarks are more applicable to REEFEX than SINKEX. The ERL for a particular chemical represents the lower 10th percentile of observed toxicity effects of all chemicals when the chemical is present [14]. The ERM represents the median concentration of the chemical in samples that were toxic. The ERL represents the value at which toxicity may "begin to occur in the [most] sensitive species" [17]. Because there is a significant degree of correlation between individual chemicals in the studies conducted to determine the ERL and ERM benchmarks, there is uncertainty about the cause of toxicity and the confidence of individual ERL and ERM values to predict toxicity for individual chemicals. There is a relatively weak relationship between toxicity and the benchmarks for Ni, Hg, and total PCB so the sediment benchmarks should be used with caution [14]. The benchmarks for Ni had the lowest incidence of effect (toxicity was generally over predicted [14]).

Possibly the greatest difference between the shallow and deep reefs is the food chains present at the sites. The relative lack of epibenthic organisms present on the ex-AGERHOLM compared to the dense growth present on the ex-VERMILLION, could be attributed to the lack of primary producers and epibenthic larvae for recruitment at the deep ocean site, which are abundantly plentiful in shallow, coastal waters. Since the reef community is the primary route of exposure for contaminant accumulation at shallow water reefs, sediment accumulation would not be as important for assessing risk as the direct accumulation by reef dwelling organisms. Another source of uncertainty is that the SINKEX study consisted of only a single vessel, so it is unknown how representative the ex-AGERHOLM is of other ex-warships. At the very least, the SINKEX sediment data provide an indication of the relative magnitude and types of chemicals that could be released into the surrounding environment from a "typical" ex-warship.

Estimates of water and tissue concentrations based on steady state leaching showed that water exposure and tissue levels of PCB were very low (Table 2) which indicates negligible exposure from contact with surface water at the reef [6]. The leach rates reported by [7] were applied to the mass of PCBs present on the ex-VERMILLION to derive the release rate $a(t)$ (Table 3A). These leach rate values represent the maximum PCB release for PCB molecules present in the solid up to the weight fraction in the solid tested, and includes the effect of transport being inhibited by the solid matrix (stationary phase) in which the PCBs reside. This is why the rate is expressed as shipboard-solid-specific and normalized to the mass of shipboard solid tested, rather than to the mass of PCBs in the solid tested (Table 3B).

The highest leach rate was for oils and greases, because the leaching rate of pure Aroclor 1254 was used as a proxy for PCBs in oils and greases. The leaching of PCBs from oils and greases was obtained by assuming that all the PCBs within oils and greases were present as Aroclor 1254 and that the Aroclor leached at the same rate as the pure Aroclor measured in the laboratory leaching experiment. This overestimates the leaching, because pure Aroclor 1254 probably has a higher leach rate than Aroclor 1254 dissolved in oils and greases. It represents the highest possible leaching, if PCBs were present in non-mobile, non-soluble, non-dispersing residual oils and greases. The lack of empirical data on PCB leaching in oils and greases was identified as a major source of uncertainty in the model.

The steady state model assumed that there is no loss of PCB from adsorption, degradation, bioaccumulation, or partitioning, but simply focuses on the maximum "available" PCB released into the environment (all other loss terms are set to zero, Fig. 3). This greatly simplifies the modeling exercise and allows the relative importance of leaching from the solid materials on the ship to be evaluated. More detailed model constructs are needed to evaluate PCB fate and potential effects in the environment and the development of such models [13, 19] was beyond the scope of this screening level ecorisk assessment.

The mass of the solid materials containing PCBs on the ex-VERMILLION was obtained by multiplying the estimates for the ex-AGERHOLM by a scale factor of 3.33 to account for greater size of the ex-VERMILLION. This imparts uncertainty to the loading estimates, because there are fundamental differences in the materials present on a troop transport ship (noncombatant) versus a destroyer (combatant). Because the ex-VERMILLION was a troop transport ship, there is more berthing areas, ducts, vents, etc. on the ex-VERMILLION (per unit volume) than the ex-AGERHOLM, therefore, scaling by volume may underestimate the total amount of felt gaskets and other comfort materials like bulkhead insulation. Conversely, cabling and oils and greases may be overestimated because there are more electrical and power plant systems per unit volume on a destroyer.

When the ex-VERMILLION and other similar ships were prepared for sinking in the 1980's, SCDNR was not aware that solid materials containing PCBs were present onboard the vessel. Therefore, no effort was made to remove specific materials for this reason. The vessel was prepared to acceptable standards for artificial reef construction activity in the U.S. at that time [20]. All commonly encountered potential shipboard pollutants such as fuels, oils, solid or liquid chemicals, liquid PCBs (electrical transformers and switchboards), and floatable materials such as plastics or wood were removed and properly disposed of by the contractor. To facilitate use of the ship in 110 feet of water and minimize its risk as a possible hazard to navigation, the overall height of the vessel was reduced to no greater than 55 feet (17 m) above the keel. All structure above the O1 level was removed. Large holes were cut in the sides of the ship and between watertight bulkheads. Removing or welding internal doors and hatches open further breached internal watertight integrity (Fig. 7). After final inspection by U.S. Coast Guard Marine Safety Office Wilmington, the vessel was towed to its final destination and sunk by the use of explosive charges set by U.S. Navy Explosive Ordnance Disposal personnel (EOD Mobile Unit Six). The Vermillion sank quickly, and settled in an upright position on barren flat sand bottom 110 feet (33 m) deep, approximately 32 nautical miles southeast of the port of Georgetown, SC (Fig. 2). Today the Vermillion Reef remains a viable reef environment supporting a diverse array of reef fishes and invertebrates (Fig. 8) and it is a desirable destination for sports fishers [12] and divers.

The main sources of uncertainty for the tissue screening were the limited amount of data for screening, the uncertainty about the tissue benchmarks, the assumptions required to assess dietary exposure, and the applicability of reference and background data. There were no data available to screen tissue concentrations for PAHs, Ag, As, Hg, and Zn. Quantitative data were available for the screening but the data were only from a single study (except for the supplemental fish sampling for PCBs) and the data were limited to 2 samples for fish and less than 10 invertebrate samples from the Navy vessel reef group. Additionally, hazard quotients and hazard indices do not take into account biological availability and other site-specific factors. While exceeding an HQ=1 or HI=10 in the reference area has little to do with risk from the sunken ship, these metrics presumably reflect the background risk and the difference between the reference and target reefs is the incremental or potential increase in risk that could be attributed to the presence of a sunken ship. Due to the conservative estimates used in the screening analysis, it is very unlikely that potential risks were under estimated.

Fig 7. The ex-VERMILLION prior to sinking.

V CONCLUSIONS

A screening-level ecorisk assessment was conducted on data from artificial reefs located off the coast of South Carolina to assess the potential risk of contaminants that could be released from sunken Navy vessels. The conclusions were based on evidence of potential ecological harm, evidence of exceeding reference and background levels, and the degree to which data were available to support the assessment. The screening level assessment found that the risk of sediment exposure was negligible for PCBs, PAHs, Cr, Hg, and Pb; low for Ag and Zn; medium for Cd and Cu; and adverse for Ni. Because the sediment benchmarks for Ni are overprotective [14], the finding of adverse exposure for Ni may be overly conservative. The data reliability for the sediment screening was good, but there was a fair amount of uncertainty associated with the sediment screening due to extrapolating from the deep ocean SINKEX site, so there was a medium level of confidence in the conclusions.

Tissue residue data showed that exposure to PCBs, Pb, and Cd in tissues of fish and PCBs and Pb in invertebrates were higher in samples from ex-Navy ship reefs than reference reefs, but most of the residue data were below effects levels for the reef community suggesting that there was negligible to low risk of exposure to demersal fish and reef invertebrates. For food chain receptors most data for contaminant concentrations in prey were below dietary benchmarks suggesting that there is low risk of exposure to dolphins and fish eating birds, and negligible risk of exposure to diving birds. There was high confidence of negligible to low risk of exposure to PCBs because supplemental fish sampling and analysis for PCBs was conducted for the assessment. Owing to limited data available for screening, the confidence in the conclusions for the other chemicals of concern was low.

Results from the empirical leaching studies and hypothetical steady state model were used to evaluate the consequences of removing materials from the ship to reduce PCB loading. For the average loading scenario, the greatest reduction in potential PCB release would be gained by removing bulkhead insulation. Because considerably more effort is required to remove certain types of materials than others, removing relatively small quantities of bulkhead insulation and using extra care to clean up oils and greases in areas where they may of come into contact with PCBs would greatly reduce the amount of PCBs leached and further reduce potential risk of exposure to PCBs. Based on the finding of negligible to low ecological risk of exposure to PCBs, creating artificial reefs with former Navy vessels containing PCBs in solid materials will not pose an unacceptable risk to the environment.

ACKNOWLEDGMENTS

This work was the result of the interagency REEFEX Technical Working Group, consisting of representatives from the U.S. EPA, the U.S. Navy, and the South Carolina Department of Natural Resources. The authors especially thank L. Casey of U.S. EPA Office of Pollution Prevention and Toxic Substances and L. Phillips of Versar Inc. for technical assistance and critical reviews of this work. This work greatly benefited from the technical contributions made by A. Lunsford, T. Scarano, T. Pape, A. Roberts, J. Garrison, M. Goodrich and other members of the REEFEX Working Group. The final reports, supporting documents, and proceedings of the REEFEX Technical Working Group can be accessed at http://environ.spawar.navy.mil/reefex.

REFERENCES

[1] M. Bell, "Marine artificial reefs. what is an artificial reef?" South Carolina Department of Natural Resources, 2001. http://water.dnr.state.sc.us/marine/pub/seascience/artreef.html

[2] T. Enemark, "The tourism aspects of artificial reefs: the nine fundamental lessons," Artificial Reef Society of British Columbia, 1999. http://www.artificialreef.bc.ca/

[3] R. Hess, D. Rushworth, M. V. Hynes, J. E. Peters, Disposal options for ships. Rand Corporation, ISBN: 0-8330-3014-0 MR-1377-NAVY 2001, 148 pp. http://www.rand.org/publications/MR/MR1377/.

[4] U.S. EPA, "Disposal of polychlorinated biphenyls (PCBs); final rule", Federal Register: June 29, 1998 (Volume 63, Number 124) http://www.access.gpo.gov/su_docs/fedreg/a980629c.html

[5] R.M Martore, T.D. Mathews, and M. Bell, "Levels of PCBs and heavy metals in biota found on ex-military ships used as artificial reefs," Marine Resources Division, South Carolina Marine Resources Center, South Carolina Department of Natural Resources, Charleston, SC, unpublished.

[6] R.K. Johnston, et al. (in press). A screening level ecorisk assessment for using former navy vessels to construct artificial reefs, Final Report, Space and Naval Warfare Systems Center, San Diego, CA, in press. http://environ.spawar.navy.mil/reefex

[7] R. George, and C. In, Investigations of polychlorinated biphenyl (PCB) release-rates from selected shipboard solid materials under laboratory-simulated shallow ocean (artificial reef) environments, Space and Naval Warfare Systems Center, San Diego, CA, in press.

[8] J.L Hyland, et al. Environmental quality of estuaries of the Carolinian Province: 1995, NOAA Tech Memorandum NOS ORCA 123 NOAA/NOS, Silver Spring, MD, 1998, 143 p. http://www.epa.gov/emap/html/pubs/docs/groupdocs/estuary/ssum/cpabs95.html

[9] R.K. Johnston, Assessing the ecological risk of toxic chemicals on coastal and estuarine ecosystems, Doctoral Dissertation, University of Rhode Island, 1999, 299pp.

[10] S.D. Dyer, C. White-Hull, and B.K. Shephard, "Assessments of chemical mixtures via toxicity reference values overpredict hazard to Ohio fish communities". ES&T 34: 2518-2524, 2000.

[11] US Army Corps of Engineers, Environmental residue-effects database, Environmental Laboratory, Vicksburg, MS, 2002. http://www.wes.army.mil/el/ered

[12] Navy Environmental Health Center, A human health risk assessment for potential exposure to polychlorinated biphenyls (PCBs) from sunken vessels used as artificial reefs (food chain scenario), Norfolk, VA, Final Report, in press.

[13] R. Gauthier, et al. Risk assessment of the potential release of PCBs and other contaminants from sunken navy ships in the deep ocean: ex-USS AGERHOLM, Final Report, Space and Naval Warfare Systems Center, San Diego, CA., in press.

[14] E.R. Long, D.D. MacDonald, S.L. Smith, and F.D. Calder, "Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments," Environmental Management, 19:1 pp81-97, 1995.

[15] John J. McMullen Associates, Weight estimates for PCBs and selected metals sunk on Ex-USS AGERHOLM (DD 826) for the deep water sunken ship study, prepared by John J. McMullen Associates, Arlington, VA, unpublished.

[16] Skidaway Institute of Oceanography, South Atlantic bight synoptic offshore observational network, 2002. http://www.skio.peachnet.edu/projects/sabsoon_web/index.html

[17] M.F. Buchman, NOAA Screening Quick Reference Tables (SQuiRT), NOAA HAZMAT Report 99-1, Seattle, WA, Coastal Protection and Restoration Division, NOAA, 1999, 12pp. http://response.restoration.noaa.gov/cpr/sediment/squirt/squirt.html

[18] B.K. Shepard, "Quantification of ecological risks to aquatic biota from bioaccumulated chemicals," in National Sediment Bioaccumulation Conference Proceedings, EPA 823-R-98-002, US EPA, Office of Water, Washington, DC, pp2-31–2-52, 1998. http://www.epa.gov/waterscience/cs/shep-d2.pdf

[19] M. S. Goodrich, J. Garrison, P. Tong, and A. Lunsford, "Risk assessment model for evaluating ex-Navy vessels as reef material," in Proceedings of the Second International Conference on Remediation of Contaminated Sediments, Venice, Italy, 2003, in press.

[20] R.B. Stone, National artificial reef plan, NOAA Technical Memorandum NMFS OF-6, 1985, 110 pp.

Fig. 8. Demersal fishes on the Vermillion Reef.